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Energy Procedia 88 (2016) 675 – 681

Energy

Procedia

CUE2015-Applied Energy Symposium and Summit 2015: Low carbon cities and urban energy systems

Polarization based charging time and temperature rise optimization for lithium-ion batteries

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Abstract

The Lithium-ion battery fast charging issues have become the bottleneck of its application as rapid development of electric vehicles. This paper developed a polarization based charging time and temperature rise optimization strategy for lithium-ion batteries. The enhanced thermal behavior model is introduced to improve the accuracy at high charging current, in which the relationship between the polarization voltage and charge current is addressed. Genetic algorithm (GA) is employed to search for the optimal charging current trajectories. The effects of charging time and temperature rise weight coefficients on battery charging performance is discussed. The charging time of the optimized charging pattern is reduced by 50%, and the temperature rise is almost identical compared to 1/3C constant current-constant voltage (CC-CV) charging pattern, balancing the battery life and charging speed.

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Peer-review under responsibility of the organizing committee of CUE 2015

Keywords: Polarization, temperature rise, charging optimization, Lithium-ion batteries

1. Introduction

Electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) have been rapidly developed in recent years driven by the need to curb air pollution caused by petroleum-based vehicles. Compared to internal combustion engine (ICE) fueled directly; power battery charging is much more complicated due to its slow charging speed and unclear effects of the charging method on battery life. The Lithium-ion battery fast charging issues have become the bottleneck of its application. The optimal charging technology is one of the difficult hotspots in the field of EVs and PHEVs.

Kinds of charging methods were reported in recent years in which aim to improve charging speed, enhance charging performance and maximize battery life. Methods for battery charging optimization can be categorized as improved charging current waveforms based methods [1], battery model based methods

[2], polarization based methods [3] and enhanced battery material based methods[4]. Improved charging current waveforms based methods is simple to control and facilitate implementation, however, they are lack of theoretical foundation in choosing battery charging current, which are for the targets to enhance charge efficiency and charge speed. Battery model based methods can predict the charging current employing the proposed battery models. They can combine battery external electrical behavior with internal reaction mechanisms, searching for optimal charging currents. However, they have difficulty in accurate parameters estimation and update, especially for the effects of battery temperature and fading. Polarization based methods provide the acceptable charging current of the lithium-ion batteries with constraints of battery polarization voltage. The polarization modelling and its quantitative effects on battery life need to be further investigated. In the enhanced battery material based methods, the stability and safety of the battery are to be further examined, which can't be applied in electric vehicles in the short term.

Temperature has significant effects on lithium-ion battery performance and lifetime. The battery activity increases as the temperature increases. But if the temperature increases over allowable limits, the stability of battery cathode lattice structure is getting worse, which not only accelerates battery degradation, but also results in battery safety issues. An accelerated aging at 40°C in thermal cycling for LMO batteries was observed, in which resulted in extra loss of active material loss in both electrodes besides generalized loss of lithium inventory and inhibited kinetics[5]. During rapid charging, the temperature gradient will inevitably increase since the average charging current is enlarged, leading to lifetime decrease if operated in unreasonable thermal excursions. In our previous study [6], the acceptable charging current curve is pursued in accordance with lithium-ion battery polarization voltage behaviors. The proposed charging curve can prevent the polarization from being out of range, conducive to increasing charging capacity and charging speed. This paper focuses on temperature rise constraint analysis, optimal charging strategy, and reliable algorithm towards optimized charging pattern.

2. Enhanced thermal behavior model

2.1. Characterization of charging temperature rise

The test platform is built to investigate the characteristics of the battery temperature rise at various charging rates. In the experiments, the battery was placed in the adiabatic box which have insulation properties, preventing heat exchange of the battery inside from external environment. Thus the measured temperature can perform the generated charging heat to maximum extent. In this study, the battery cell chemistry is comprising positive electrode $\text{LiMn}_{1/3}\text{Ni}_{1/3}\text{Co}_{1/3}\text{O}_2 + \text{LiMn}_2\text{O}_4$ composite and graphite as negative electrode. The nominal capacity is 25Ah. The initial SOC in the experiment is 0%.

The battery temperature rise profiles at different charging rates are shown in Figure 1. From Figure 1, it is found that the maximum temperature rise appears at the positive electrode tab and the minimum temperature rise appears at the negative electrode tab. The temperature rise on the surface of the battery is uniform. The temperature rise in the incubator is less than 1°C. When the battery is under the constant voltage charging mode, the temperature turns decreasing. The temperature increases smoothly when the charging current is 2C, but the temperature increases with an obvious fluctuation when the charging current is 1C and 1.5C. Even at the initial state of charging, the temperature decreases. This is because during the charging process, entropy coefficient varies. Sometimes it is positive and sometimes it is negative. Thus, both endothermic reactions and exothermic reactions happen in the battery resulting in the temperature rise fluctuate. In the initial charging process, the entropy change coefficient is negative and large, the battery reactions absorb heat, resulting in temperature decrease. However when the charging

current is 2C rate, polarization heat and joule heat take a large proportion of the generated heat and the heat generated by entropy change takes a small proportion. Thus, the temperature rise doesn't fluctuate.

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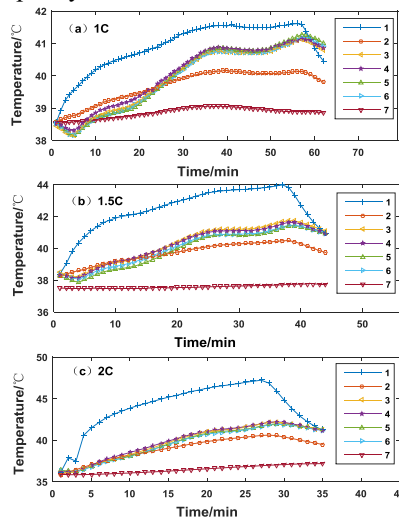


Fig. 1. Battery temperature rise profiles at different charging rates

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2.2. Enhanced thermal behavior model

As discussed in section 2.1, the battery surface has a uniform temperature when the charge current is within 2C, the battery can therefore be seen as a particle cell for the thermal model. Using the enhanced thermal model, the sampling time interval is 1s, the battery temperature at time k can be expressed by:

$$T_{cell,k} = T_{cell,k-1} + \frac{I^2 R_{\Omega} + IU_p + T_{cell,k-1} I \frac{\partial E}{\partial T_{cell}} - Ah(T_{cell,k-1} - T_{amb})}{mC_{cell}} \quad (1)$$

Where U_p is cell polarization voltage, and expressed as $U_p = kI + b$, m is the weight of battery. The initial temperature is 25°C in the study.

The simulated and experimental results for battery temperature during charge is illustrated in Figure 2, where represents the simulated results with the DC resistance to calculate the overpotential heat, expresses the simulated charging temperature based on the improved thermal model. It is indicated that the simulation results of both methods are almost identical with each other at the charge current of 1C, and the maximum error is approximately 0.9°C. The simulation error of the method is within 1.7°C at the charge current of 2C. The accuracy is remarkably improved compared to the DC resistance calculation method with the maximum error of 2.7°C. This is because that the polarization resistance is not a constant, but decreasing to some extent as the charge current increase. The estimation error with DC resistance calculation method is small at the low charge current, nevertheless, the constant DC resistance can not effectively express battery polarization characters, resulting in larger errors at high charge currents. It is indicated that the proposed method can describe the relationship between polarization voltage and the current, demonstrating high thermal simulation accuracy.

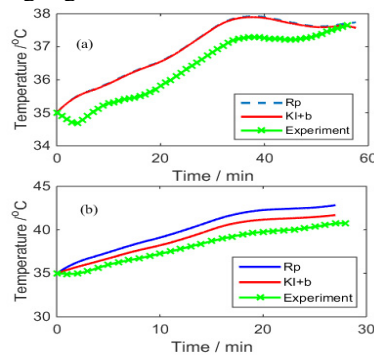


Fig. 2. Battery temperature rise profiles at different charging rates

The simulated and experimental results for battery temperature during charge is illustrated in Figure 2, where represents the simulated results with the DC resistance to calculate the overpotential heat, expresses the simulated charging temperature based on the improved thermal model. It is indicated that the simulation results of both methods are almost identical with each other at the charge current of 1C, and the maximum error is approximately 0.9°C. The simulation error of the method is within 1.7°C at the charge current of 2C. The accuracy is remarkably improved compared to the DC resistance calculation method with the maximum error of 2.7°C. This is because that the polarization resistance is not a constant, but decreasing to some extent as the charge current increase. The estimation error with DC resistance calculation method is small at the low charge current, nevertheless, the constant DC resistance can not effectively express battery polarization characters, resulting in larger errors at high charge currents. It is indicated that the proposed method can describe the relationship between polarization voltage and the current, demonstrating high thermal simulation accuracy.

3. The proposed optimal charging strategy

3.1. Theoretical analysis

Taking account of battery charge polarization and temperature rise constraints, the optimized charging strategy is summarized in the following aspects. First, taking the acceptable charge current as the optimal charge current limit, the battery is charged with high current at the initial charging stage to speed up the charging process. Small charge current is employed at the end of charging to decrease battery polarizations, and to be charged more capacities. Meanwhile, the temperature rise of the battery can also be restricted, preventing from thermal runaway and improving charge safety. The ohmic resistance, polarization resistance and entropy change coefficient of the battery are varying as SOC increase, leading to the charge temperature rise rate differing among various SOC regions. Second, considering charge temperature rise characters at different SOC region, the charge current can be augmented at SOC regions with lower temperature rise, on the contrary, the charge current is decreased. The charge current and temperature rise can consequently be optimized at the whole SOC region, balancing battery lifetime and charging speed.

The total charging time and temperature rise are two parameters to be optimized based on the proposed charging strategy. The optimization target is to speed up the charging process and reduce the charging temperature rise, realizing the balance between the two parameters. The fitness function is consequently expressed by the following equation.

$$F(t, \Delta T) = \alpha \left[\frac{40}{t_{max} - t_{0.05C}} (t - t_{0.05C}) + 60 \right] + \beta \left[100 + \frac{40(\Delta T - \Delta T_{0.05C})}{\Delta T_{0.05C} - \Delta T_{max}} \right] \quad (2)$$

$\alpha + \beta = 1$

Where α and β are weight coefficient of charging time and temperature rise, respectively. t_{max} represents the total charging time when the battery is charged with the acceptable current. $t_{0.05C}$ is the charging time at the current of 0.05C. $\Delta T_{0.05C}$ is the battery temperature rise when charged at the current of 0.05C. The linear weight method is used to calculate the fitness values.

3.2. Optimal charging current estimation by genetic algorithm

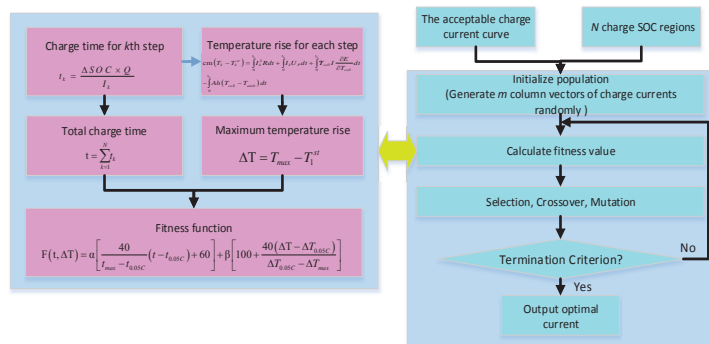


Fig. 3. The flowchart of charge current estimation with GA method Copyright

The flowchart of optimal charge current estimation using GA method is shown in Figure 3, and the specific procedure is summarized as follows. Initial population are first produced as the basic currents. In the process, column vectors with N charging currents are randomly generated based on the acceptable charge currents limit. Second, fitness values are calculated, in which the charging time and temperature rise are regarded as the optimization objectives. And then the selection operator, recombination operator, and mutation operator are carried out in the population to optimize the parameters. Finally, the procedure

will be ended when meeting the termination criterion. Actually each SOC segment has m optional charge currents, thus will have charging current permutations for the whole charging process. Each permutation has a fitness values, and the charging current permutation with the highest score will be finally selected.

4. Results discussion for the optimal charging strategy

The optimization results at various weight coefficients is illustrated in Figure 4 and Table 1, where α and β represent weight coefficients of charging time and temperature rise, respectively. It is shown that the maximum fitness value of every generation approximately trends to be stable when the reproduction generations of the GA getting 40, indicating that the fitness function is convergent. The overall variation tendency of the optimal charging current at various weight coefficients is decreasing gradually since the acceptable charge current is declining as SOC increase, however in some SOC ranges, the charging current increases resulting from smaller resistance in this SOC range. When $\alpha:\beta=3:7$, the charging time of the optimal current is 1.99h, and the temperature rise 1.9°C. When $\alpha:\beta=7:3$, the charging time of the optimal current is 1.07h, and the temperature rise 3.8°C. With various weight coefficients, the optimization results will have different charging time and charging temperature rise. Charging time will decrease with a high value of α and a small value of β . On the contrary, the charging temperature rise will decrease.

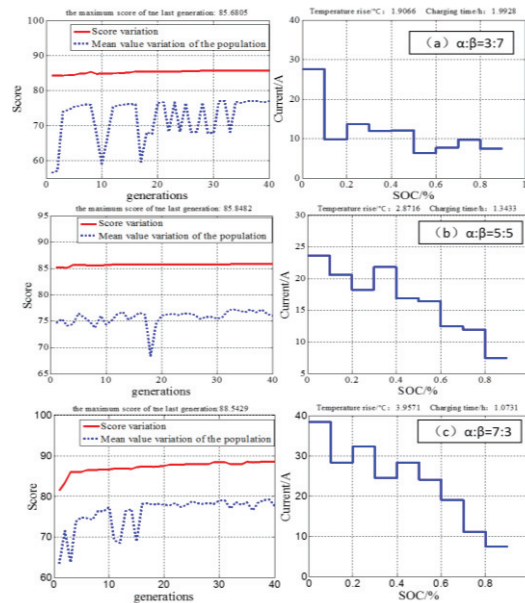


Fig. 4. Optimization results of charging current at various weight coefficients (a) $\alpha:\beta=3:7$; (b) $\alpha:\beta=5:5$; (c) $\alpha:\beta=7:3$ Authors keep full copyright over papers published in Energy Procedia

From the experiment results, it can be found that the charge time and temperature rise can be optimized at the whole SOC region using the proposed method. The polarization is decreased during the charging process with the proposed charging strategy, more capacity can be charged, balancing the charging capacity and charging time. With low temperature rise and polarization level, the proposed charging pattern can also inhibit battery degradation.

Table 1. Experimental comparisons of the proposed and typical charging patterns

$\alpha:\beta$	Charging pattern	Total charge time /s	Total charge capacity /Ah	charge time to 4.2V /s	charge capacity to 4.2V /Ah	Temperature rise /°C
3:7	Proposed	7364	19.961	6960	19.487	1.0
	Average charge rate CCCV	7466	20.084	7017	19.559	1.3
5:5	Proposed	5347	20.694	4931	20.21	1.2
	Average charge rate CCCV	5117.6	20.027	4294.35	18.715	1.3
7:3	Proposed	3938	19.912	3520	19.428	3.8
	Average charge rate CCCV	4263	20.084	3219.38	18.305	3.7
	1/3C CCCV	10089.63	20.661	8997.04	18.742	1

5. Conclusions

This paper presented an optimal charging strategy to balance the charging speed and battery life, in which the charging time and temperature rise are for the target, the polarization is for the constraint. The experimental results indicate that the proposed charging pattern can reduced charging time remarkably with reasonable temperature rise, demonstrated its efficacy. The weight coefficients have important effects on battery charging performance, and their optimization will be further investigated in the future.

Acknowledgement

This work was supported by the National Key Technology Research and Development Program of China under Grant 2013BAA01B03) and National Natural Science Foundation of China under Grant 51277010.

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